

Test of T violation in neutral B decays ¹

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Abstract

T violation should be tested independently of CP violation. Besides K system, B meson decays provide another good place to study T violation. In the Standard Model, T violation in $B^0 \rightleftharpoons \bar{B}^0$ oscillation is expected to be small. The angular distribution of $B \rightarrow VV$ decay permits one to extract the T-odd correlation. In the absence of final state interaction, T violation in $B \rightarrow J/\psi(l^+l^-)K^*(K_S\pi^0)$ decay can reach 4 – 7% via $B^0 - \bar{B}^0$ mixing.

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1. Introduction

Under the assumption of CPT invariance, the observed CP violation in neutral K decays demonstrates T violation in weak decays. However, T violation and CP violation are different physics concepts. CP violation requires the partial rate difference of the particle and its antiparticle while T violation needs the partial difference between the decay process and its time reversed process. The evidence for T violation based on CP violation and CPT invariance is indirect. The test of T violation should be done independently of CP violation.

Recently, CPLEAR collaboration gives the first direct observation of T violation in the difference of probability between $K^0 \rightarrow \bar{K}^0$ and $\bar{K}^0 \rightarrow K^0$ in the limit of CPT symmetry and the validity of $\Delta S = \Delta Q$ rule [1]. Moreover, KTeV observed another evidence of T violation in the planar-angle asymmetry in the $K_L \rightarrow \pi^+\pi^-e^+e^-$ decay [2]. Although the validity of T violation in these two decays was questioned by [3], we expect the future experiments can exclude some questions about T violation. Up to now, the study of T violation is mainly in K decays. It is well-known that B meson decays can provide another good place for testing CP violation. If the CPT invariance holds, T violation should be exactly equal to CP violation. Since CP violation in neutral B decays can be large ($\mathcal{O}(1)$), the large T violation may happen in B decays. So it is necessary to study T violation in B decays.

For the weak decay process $i \rightarrow f$, T violation is defined by $\Delta_T \equiv \frac{\Gamma(f' \rightarrow i') - \Gamma(i \rightarrow f)}{\Gamma(f' \rightarrow i') + \Gamma(i \rightarrow f)}$ where $f' \rightarrow i'$ is the reversed process and the prime denotes the reverse of spin and momentum. In general, it is difficult to implement the reversed weak decay. One reason is that it is impossible to set up the initial condition [4] such as in nuclear beta decay. The other reason lies in that the weak decay is so weak that it is unable to extract the reversed weak decay from the strong and electromagnetic backgrounds. The reversed reaction of $B^0 \rightarrow \pi^+\pi^-$ is such an example. The only exception is the neutral particle oscillation induced by weak interaction such as $K^0 \rightleftharpoons \bar{K}^0$ and $B^0 \rightleftharpoons \bar{B}^0$. We shall discuss T violation in $B^0 \rightleftharpoons \bar{B}^0$ oscillation without or with the assumption CPT invariance in this paper. For the latter case, T violation in $B^0 \rightleftharpoons \bar{B}^0$ oscillation is predicted to be small in the Standard Model (SM).

Another way to observe T violation is to measure the T-odd correlations in the final states of weak decays. A T-odd correlation is one that changes sign under the reverse of all incoming and outgoing three momentum and polarization. One classic example is the triple T-odd correlation $\sigma_{\mathbf{n}} \cdot (\mathbf{k}_{\mathbf{p}} \times \mathbf{k}_{\mathbf{e}})$ of the nuclear beta decay where $\sigma_{\mathbf{n}}$ is the spin of the neutron and $\mathbf{k}_{\mathbf{p}}$, $\mathbf{k}_{\mathbf{e}}$ are the three momentum of proton and electron. Whether the T-odd observable is considered as T violation should be viewed with caution. There is a mimicry of T violation caused by final state interaction (often refers to strong interaction) even if the fundamental interactions is time reversal invariant. Wolfenstein calls it "pseudo Time Reversal Violation (pseudo TRV)". In [5], the authors prove that using the unitarity constraint and CPT invariance of final state interaction, the T-odd effect can be identified with a measurement of T violation if the final state interaction effects are small and negligible. According to [6], the correlation between the meson and lepton plane in $K_L \rightarrow \pi^+ \pi^- e^+ e^-$ decay is T-odd and thus violates time reversal symmetry. The same method is used in [7] to study the angular distribution of $B \rightarrow K^- \pi^+ e^+ e^-$ and $B \rightarrow \pi^- \pi^+ e^+ e^-$. Their results show that T violation is small. In the differential angular distribution of the decay $B \rightarrow V_1 V_2$ where $V_{1,2}$ represent two vector mesons, the interference terms contain T-odd correlation contribution. If ϕ is the angle between the decay planes of the two vectors, the angular correlations $\sin 2\phi$ and $\sin \phi$ terms are T-odd. In this paper, we intend to study T violation in $B \rightarrow VV$ decays using the angular distribution analysis. The final state interaction effects is also taken into account in the T-odd observable.

2. T violation in $B^0 \rightleftharpoons \bar{B}^0$ oscillation

The $\Delta B = \pm 2$ weak decay via Box diagram causes the mixing between B^0 and \bar{B}^0 . The physical states are the superposition of the flavor states $|B^0\rangle$ and $|\bar{B}^0\rangle$. The two mass eigenstates in neutral B_d system can be generally written by

$$\begin{aligned} |B_1\rangle &= \frac{1}{\sqrt{|p_1|^2 + |q_1|^2}} [p_1 |B^0\rangle + q_1 |\bar{B}^0\rangle] \\ |B_2\rangle &= \frac{1}{\sqrt{|p_2|^2 + |q_2|^2}} [p_2 |B^0\rangle - q_2 |\bar{B}^0\rangle] \end{aligned} \quad (1)$$

In the neutral K system, the mixing parameter p_i, q_i are usually represented by small parameters of ϵ, Δ . This parameterization method is not suitable to apply in neutral B system because CP and T violation in it is predicted to be large in CKM model. We take the exponential parameterization as given in [8]. Thus the mixing parameters p_i, q_i are related by

$$\frac{q_1}{p_1} = tg\frac{\theta}{2}e^{i\phi}, \quad \frac{q_2}{p_2} = ctg\frac{\theta}{2}e^{i\phi} \quad (2)$$

where θ and ϕ are complex phases in general. According to [8], T violation requires $\phi \neq 0$.

The time evolution of the initially $|B^0\rangle$ or $|\bar{B}^0\rangle$ after a proper time t is

$$\begin{aligned} |B^0(t)\rangle &= g_+(t)|B^0\rangle + \bar{g}_+(t)|\bar{B}^0\rangle \\ |\bar{B}^0(t)\rangle &= g_-(t)|\bar{B}^0\rangle + \bar{g}_-(t)|B^0\rangle \end{aligned} \quad (3)$$

where

$$\begin{aligned} g_{\pm}(t) &= e^{-im_B t - \frac{1}{2}\Gamma_B t} [ch(\frac{ix-y}{2}\Gamma_B t) \pm cos\theta sh(\frac{ix-y}{2}\Gamma_B t)] \\ \bar{g}_{\pm}(t) &= e^{-im_B t - \frac{1}{2}\Gamma_B t} sin\theta e^{\pm i\phi} sh(\frac{ix-y}{2}\Gamma_B t) \end{aligned} \quad (4)$$

with $x \equiv \frac{\Delta m_B}{\Gamma_B}$, $y \equiv \frac{\Delta\Gamma_B}{2\Gamma_B}$.

The T violation in $B^0 \rightleftharpoons \bar{B}^0$ oscillation is defined as

$$A_T(t) \equiv \frac{P_{B^0(t) \rightarrow \bar{B}^0} - P_{\bar{B}^0(t) \rightarrow B^0}}{P_{B^0(t) \rightarrow \bar{B}^0} + P_{\bar{B}^0(t) \rightarrow B^0}} = \frac{|e^{i\phi}|^2 - |e^{-i\phi}|^2}{|e^{i\phi}|^2 + |e^{-i\phi}|^2} = -2Im\phi \quad (5)$$

From Eq.(5), $A_T(t)$ is independent of t . It is a constant number. This is the same as the case in the CPLEAR experiment. Moreover $A_T(t)$ is not related with the CPT violation parameter θ . Note that $A_T(t)$ is proportional to $Im\phi$, the imaginary part of the mixing parameter ϕ . As it will be seen later, T violation in the interference of the $B^0 - \bar{B}^0$ mixing and the decay amplitude requires $Re\phi \neq 0$.

The experimental test of T violation $A_T(t)$ can be determined in the semileptonic decay and the same-sign dileptonic ratios of B decays through [9]

$$A_T(t) = \frac{\Gamma(B^0(t) \rightarrow \bar{X}l^-\nu) - \Gamma(\bar{B}^0(t) \rightarrow Xl^+\nu)}{\Gamma(B^0(t) \rightarrow \bar{X}l^-\nu) + \Gamma(\bar{B}^0(t) \rightarrow Xl^+\nu)} = \frac{N^{++} - N^{--}}{N^{++} + N^{--}} = -2Im\phi \quad (6)$$

where N^{++} , N^{--} are the same-sign dilepton events. In Eq.(6), The validity of $\Delta B = \Delta Q$ rule is assumed.

We next turn to discuss the SM expectation of the A_T . In SM, CPT is invariant, and the origin of CP and T violation lies in the nonzero complex phase in CKM matrix. The mixing parameter θ in Eq.(2) will be equal to $\frac{\pi}{2}$. Thus, $\frac{g_1}{p_1} = \frac{g_2}{p_2} = \frac{g}{p}$. According to [10],

$$|\frac{g}{p}| - 1 = |e^{i\phi}| - 1 = \frac{1}{2}Im\frac{\Gamma_{12}}{M_{12}} \sim \mathcal{O}(10^{-3}) \quad (7)$$

Thus

$$A_T(t) \approx Im\frac{\Gamma_{12}}{M_{12}} \sim \mathcal{O}(10^{-3}) \quad (8)$$

The above estimate is based on the assumption that the box diagram with a cut is appropriate to calculate Γ_{12} . The uncertainty from the use of quark diagram to describe Γ_{12} could be a factor of 2-3.

3. T violation in the angular distribution of $B \rightarrow VV$ decay

As discussed in the Introduction, another way to observe T violation is through the T-odd correlation in the final states. Nonleptonic B decays play important role in exploring CP violation such as the decays $B \rightarrow J/\psi K_S$, $\pi\pi$, πK , etc. Unlike CP violation, there is no T-odd correlation in $B \rightarrow PP$ and $B \rightarrow VP$ decay. Because the decay amplitude contains only T-even term: the momentum square for $B \rightarrow PP$ decay; and the product of momentum and polarization vector for $B \rightarrow VP$ decay. Both of these terms are invariant under time reversal. In $B \rightarrow VV$ decays, the angular correlation between the decay planes of two vectors contains T-odd terms thus provides place to search T violation. We take $B \rightarrow J/\psi K^*$ as an example to discuss the T violation in $B \rightarrow VV$ decays.

The differential decay distribution for $B \rightarrow K^* J/\psi \rightarrow (K\pi)(l^+l^-)$ is [11]:

$$\begin{aligned} \frac{d^3\Gamma}{d\cos\theta_1 d\cos\theta_2 d\phi} &= \frac{|\vec{p}|}{16\pi^2 m_B^2} \frac{9}{8} \left\{ \frac{1}{4} \sin^2\theta_1 (1 + \cos^2\theta_2) (|H_{+1}|^2 + |H_{-1}|^2) + \cos^2\theta_1 \sin^2\theta_2 |H_0|^2 \right. \\ &\quad \left. - \frac{1}{2} \sin^2\theta_1 \sin^2\theta_2 [\cos 2\phi \text{Re}(H_{+1}H_{-1}^*) - \sin 2\phi \text{Im}(H_{+1}H_{-1}^*)] \right\} \end{aligned} \quad (9)$$

$$-\frac{1}{4}\sin 2\theta_1 \sin 2\theta_2 [\cos \phi \text{Re}(H_{+1}H_0^* + H_{-1}H_0^*) - \sin \phi \text{Im}(H_{+1}H_0^* - H_{-1}H_0^*)]]\}$$

where θ_1 is the polar angle of the K momentum in the rest frame of the K^* meson with respect to the helicity axis of K^* meson (the negative of the the direction of the J/ψ in K^* rest frame) and similarly θ_2 is the polar angle of the positive lepton l^+ (e^+ or μ^+) momentum in the rest frame of the J/ψ with respect to the helicity axis of J/ψ ; ϕ is the angle between the planes of the two decays of $K^* \rightarrow K\pi$ and $J/\psi \rightarrow l^+l^-$. In eq.(9), \vec{p} is the three momentum of the vector K^* ; H_i are the helicity amplitude defined in [11]. The angle correlations $\sin 2\phi$ and $\sin \phi$ are T-odd. To confirm this, define the unit vector $\hat{\mathbf{p}} \equiv \frac{\vec{p}_{K^*}}{|\vec{p}_{K^*}|}$. Thus,

$$\begin{aligned} \sin \phi &= \left(\frac{\vec{p}_K \times \vec{p}_\pi}{|\vec{p}_K \times \vec{p}_\pi|} \right) \times \left(\frac{\vec{p}_{l^+} \times \vec{p}_{l^-}}{|\vec{p}_{l^+} \times \vec{p}_{l^-}|} \right) \cdot \hat{\mathbf{p}} \\ \sin 2\phi &= 2 \left(\frac{\vec{p}_K \times \vec{p}_\pi}{|\vec{p}_K \times \vec{p}_\pi|} \right) \times \left(\frac{\vec{p}_{l^+} \times \vec{p}_{l^-}}{|\vec{p}_{l^+} \times \vec{p}_{l^-}|} \right) \cdot \hat{\mathbf{p}} \left(\frac{\vec{p}_K \times \vec{p}_\pi}{|\vec{p}_K \times \vec{p}_\pi|} \right) \cdot \left(\frac{\vec{p}_{l^+} \times \vec{p}_{l^-}}{|\vec{p}_{l^+} \times \vec{p}_{l^-}|} \right) \end{aligned} \quad (10)$$

From the above equation, $\sin 2\phi$ and $\sin \phi$ contain 9 and 5 momentum vectors in the products respectively. Under the time reversal transformation, they change their signs. All these momentums are defined in the rest frame of B meson.

Another form of the angular distribution based on the transversity variable is given in [12] [13]. In that form, the CP-even and odd and T-even and old component is obvious. Both the two forms are principally the same except for the adoption of different variable.

The integration over angles θ_1 and θ_2 yields the ϕ angle distribution

$$\frac{d\Gamma}{d\phi} = \frac{|\vec{p}|}{16\pi^2 m_B^2} \{ |H_{+1}|^2 + |H_{-1}|^2 + |H_0|^2 - \cos 2\phi \text{Re}(H_{+1}H_{-1}^*) + \sin 2\phi \text{Im}(H_{+1}H_{-1}^*) \} \quad (11)$$

From Eq.(11), only one T-odd $\sin 2\phi$ term is left when integrating over angles θ_1 and θ_2 . The other T-odd $\sin \phi$ term can be extracted from the full three-angle distribution or the difference of ϕ angle distribution between the same hemisphere events (e.g. $0 < \theta_1, \theta_2 < \frac{\pi}{2}$) and the opposite hemisphere events (e.g. $0 < \theta_1 < \frac{\pi}{2}, \frac{\pi}{2} < \theta_2 < \pi$). For this case, the full angle distribution is required to be known from the experiment. In this paper, we restrict our discussion in the single angle ϕ distribution given by Eq.(11) because it is easier to treat in the experiment.

So, T violation is given by

$$\Delta_T = \frac{(\int_0^{\frac{\pi}{2}} - \int_{\frac{\pi}{2}}^{\pi} + \int_{\pi}^{\frac{3\pi}{2}} - \int_{\frac{3\pi}{2}}^{2\pi}) \frac{d\Gamma}{d\phi} d\phi}{(\int_0^{\frac{\pi}{2}} + \int_{\frac{\pi}{2}}^{\pi} + \int_{\pi}^{\frac{3\pi}{2}} + \int_{\frac{3\pi}{2}}^{2\pi}) \frac{d\Gamma}{d\phi} d\phi} = \frac{2}{\pi} \frac{Im(H_{+1}H_{-1}^*)}{|H_{+1}|^2 + |H_{-1}|^2 + |H_0|^2} \equiv \frac{2}{\pi} \beta_2 \quad (12)$$

Up to now, our analysis is model independent. In the remainder of the paper, we will restrict our discussion in the Standard Model. From Eq.(12), T violation observable Δ_T is proportional to the angular correlation coefficient β_2 . This relation is a general result of the decay $B \rightarrow VV$. The nonvanishing $Im(H_+H_-^*)$ is caused by weak CKM phases or strong final state interaction phases under the condition that they contribute differently to H_{+1} and H_{-1} . First, we discuss the case that the final state interaction is absent. In [11], the authors had systematically calculated all the $B \rightarrow VV$ decays. Their result shows that β_2 is very small. For most $B \rightarrow VV$ process, β_2 is less than 10^{-4} . In the special example of $B \rightarrow K^*J/\psi$, the tree and the dominant QCD Penguin diagram have the same CKM phase, thus β_2 is nearly zero.

Second, we consider the nonvanishing β_2 caused only by strong final state interaction. Since the strong interaction is T invariant, the violation induced by final state interaction is not the true T violation but the mimicry of T violation.

Let us introduce

$$\begin{aligned} H_{||} &= \frac{1}{\sqrt{2}}(H_{+1} + H_{-1}) \\ H_{\perp} &= \frac{1}{\sqrt{2}}(H_{+1} - H_{-1}) \end{aligned} \quad (13)$$

and define the strong phase difference $\delta \equiv Arg(H_{||}H_{\perp}^*)$ then

$$\Delta_T = \frac{2}{\pi} \frac{|H_{||}||H_{\perp}| \sin \delta}{|H_{||}|^2 + |H_{\perp}|^2 + |H_0|^2} \quad (14)$$

The fact that the T violation mimicry appears to be proportional to $\sin \delta$ was revealed long time ago (see [4]). Here we again find this particular characteristic in $B \rightarrow VV$ decays. Up to now, definite quantitative analysis of final state interaction has not been accessible yet. The concrete information about strong phase is unknown. But, based on some phenomenological consideration, the final state interaction effects in $B \rightarrow K^*J/\psi$ is estimated to be small. The small width of J/ψ makes the strong coupling between J/ψ and strong states be small. Moreover,

there are few channels with large branching ratios that can transform into the final state K^*J/ψ through strong interaction. From above, it seems that T violation in the angular distribution of $B \rightarrow K^*J/\psi$ is a small effect.

There are three types of CP violation in neutral B system. CP violations in decay amplitude and mixing are small. The most important type is the CP violation in the interference of mixing and decay. This type is promising to give large CP violation. T violation in $B^0 \rightleftharpoons \bar{B}^0$ oscillation is due to $B^0 - \bar{B}^0$ mixing. T violation in the above discussion of the $B \rightarrow VV$ decay which requires weak phases contribute differently to helicity amplitudes belongs to the T violation in decay. Both of them are small. Next, we intend to seek for large T violation in the interference of mixing and decay.

In the Standard Model, the time evolution of B^0 and \bar{B}^0 is obtained from Eq.(3)

$$\begin{aligned} |B^0(t)\rangle &= f_+(t)|B^0\rangle + \frac{q}{p}f_-(t)|\bar{B}^0\rangle \\ |\bar{B}^0(t)\rangle &= \frac{p}{q}f_-(t)|B^0\rangle + f_+(t)|\bar{B}^0\rangle \end{aligned} \quad (15)$$

where $f_+(t) = e^{-im_B t - \frac{\Gamma_B t}{2}} \cos \frac{\Delta m_B t}{2}$, $f_-(t) = e^{-im_B t - \frac{\Gamma_B t}{2}} i \sin \frac{\Delta m_B t}{2}$, $\frac{q}{p} = e^{-i2\beta}$, and β is the angle of the unitarity triangle. We have neglected the width difference of two mass eigenstates.

If K^{*0} in the decay $B^0 \rightarrow K^{*0}J/\psi$ is observed to decay to CP eigenstates $\pi^0 K_S$, then angular distribution analysis gives the time dependent T violation as

$$\begin{aligned} \Delta_T(t) &= \frac{2}{\pi} \frac{\text{Im}(H_{||}(t)H_{\perp}^*(t))}{|H_{||}(t)|^2 + |H_{\perp}(t)|^2 + |H_0(t)|^2} \\ &= \frac{2}{\pi} \frac{|H_{||}(0)||H_{\perp}(0)|[\sin\delta\cos\Delta m_B t + \cos\delta\cos 2\beta\sin\Delta m_B t]e^{-\Gamma_B t}}{[|H_{||}(0)|^2 + |H_{\perp}(0)|^2 + |H_0|^2(0) + \sin 2\beta\sin\Delta m_B t(|H_{||}(0)|^2 + |H_0(0)|^2 - |H_{\perp}(0)|^2)]e^{-\Gamma_B t}} \end{aligned} \quad (16)$$

The above time dependent T violation has two contributions. The first term is the mimicry of T violation induced by final state interaction. The second term which contains $\cos 2\beta$ in the absence of final state interaction is due to the interference of mixing and decay. In this case, the small final state interaction effects can be neglected.

The time integrated T violation obtained from Eq.(16) is

$$D_T = \frac{2}{\pi} \frac{\int_0^\infty dt \text{Im}(H_{||}(t)H_{\perp}^*(t))}{\int_0^\infty dt [|H_{||}(t)|^2 + |H_{\perp}(t)|^2 + |H_0(t)|^2]} \quad (17)$$

$$= \frac{2}{\pi} \frac{|H_{||}(0)||H_{\perp}(0)|[\frac{\sin\delta}{1+x^2} + \cos\delta\cos 2\beta\frac{x}{1+x^2}]}{|H_{||}(0)|^2 + |H_{\perp}(0)|^2 + |H_0|^2(0) + \sin 2\beta\frac{x}{1+x^2}(|H_{||}(0)|^2 + |H_0(0)|^2 - |H_{\perp}(0)|^2)}$$

where $x \equiv \frac{\Delta m_B}{\Gamma_B} = 0.7$ is obtained from PDG98 [15].

In order to estimate the time integrated T violation, we use $\sin 2\beta = 0.5$ and the parameters given in [13] which based on the models of BSW, Soares and Cheng [14]. Table 1 gives the results of time integrated T violation in $B \rightarrow K^*(\pi^0 K_S)J/\psi(l^+l^-)$ with different models in the absence of final state interaction. From Table 1, one can see that different models give the T violation range from 0.04 to 0.07.

Table 1. Time-integrated T violation in $B \rightarrow J/\psi(l^+l^-)K^*(\pi^0 K_S)$ with different models

	BSW	Soares	Cheng
D_T	0.038	0.069	0.047

4. Conclusion

In this paper, we present a study of T violation in $B^0 \rightleftharpoons \bar{B}^0$ oscillation and $B \rightarrow VV$ decays. T violation in B decays opens another way to test Standard Model and the origin of CP/T violation. In $B^0 \rightleftharpoons \bar{B}^0$ oscillation, T violation induced by $B^0 - \bar{B}^0$ mixing is about the order of 10^{-3} . This tiny effects is possible to observe in semileptonic decay and dileptonic decay at B-factory and LHC-B. If a large effect is found, it will be new physics beyond the Standard Model. T violation in decay of $B \rightarrow VV$ from the interference term β_2 with different weak phases that contribute to helicity amplitudes is small, and this effect can not be extracted from the mimicry induced by final state interaction. Via interference of $B^0 - \bar{B}^0$ mixing and decay, the time integrated T violation in $B^0 \rightarrow K^{*0}J/\psi \rightarrow (K_S\pi^0)(l^+l^-)$ decay can reach 4-7% which is experimentally accessible. In this case final state interaction effects can be neglected.

From the CPT theorem, T violation should be exactly equal to CP violation. CP violation in neutral B decays can be as large as $\mathcal{O}(1)$, while T violation we had found is at the 10% level

of CP violation. So the question that how and where to find large T violation in B decays arises.

Note added: After finishing this paper, we became aware that the T-odd correlation in $B \rightarrow VV$ decays was pointed out in hep-ph/9911338 [16]. However, the physics motivation of two papers are different.

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References

- [1] CPLEAR Collaboration (A. Angelopoulos et al.) Phys.Lett.B**444**, 52-60 (1998).
- [2] J. Adams et al, Phys.Rev.Lett.**80** 4123 (1998).
- [3] I. I. Bigi, A. I. Sanda, hep-ph/9904484;
L. Wolfenstein, Phys.Rev.Lett**83** 911 (1999);
J. Ellis, N. E. Mavromatos, hep-ph/9903386.
- [4] R. G. Sachs, The Physics of Time Reversal, University of Chicago Press, Chicago, 1987.
- [5] L. Alvarez-Gaume, C. Kounnas, S. Lola, P. Pavlopoulos, hep-ph/9903458, talk given at 34th Rencontres de Moriond: Electroweak Interactions and Unified Theories, Les Arcs, France, 13-20 March, 1999.
- [6] L. M. Sehgal, M. Wanniger, Phys.Rev.D**46**, 1035 (1992); Phys.Rev.D**46**, 5209(1992).
- [7] F. Kruger, L. M. Sehgal, N. Sinha, R. Sinha, hep-ph/9907386.
- [8] M. Kobayashi, A.I. Sanda, Phys.Rev.Lett**69** 3139 (1992).
- [9] D.-S. Du, Z.-T. Wei, hep-ph/9904403.

- [10] Y. Nir, SLAC-PUB-5874, WIS-92/67/Sep-PH.
- [11] G. Kramer, W. F. Palmer, Phys.Rev.D**45**, 193 (1992).
- [12] A. S. Dighe, I. Dunietz, H. J. Lipkin, J. L. Rosner, Phys.Lett.B**369**, 144-150 (1996).
- [13] A. S. Dighe, I. Dunietz, R. Fleischer, Eur.Phys.J.C**6**, 647-662 (1999).
- [14] M. Bauer, B. Stech, M. Wirbel, Z.Phys.C**29**, 637 (1985); Z.Phys.C**34**, 103 (1987);
J. M. Soares, Phys.Rev.D**53** 241 (1996); H.-Y. Cheng, Z.Phys.C**69** 647 (1996).
- [15] PDG98, Eur. Phys. J. C**3** (1998)
- [16] C.-W. Chiang, L. Wolfenstein, hep-ph/9911338.